THE INFLUENCE OF GAMMA RADIATION ON POLARIZATION MODE DISPERSION OF FIBERS APPLIED IN COMMUNICATIONS

by

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The fiber optics technology is constantly being developed, and is becoming an essential component of contemporary communications, medicine and industry. Fibers, their connections and system components play a major role in optical signal transmission, telecommunications, power transmission, and sensing processes using fiber technology. The two main light propagation characteristics of an optical fiber are attenuation and dispersion. The possibility of controling these parameters is of utmost importance for obtaining the requested transmission quality. This paper reports on an investigation to determine the influence of gamma radiation of ^{60}Co on the variation of optical fiber propagation parameters, such as polarization mode dispersion. In addition, it also considers chosen topics in the field of fiber optics technology.

Key words: optical fiber, radiation effect, polarization mode dispersion, environmental effect, gamma irradiation

INTRODUCTION

The continuing need for larger bandwidth and capacity to support existing and advanced technologies, such as fiber-to-the-building (FTTB), fiber-to-the-home (FTTH), and Internet Protocol Television (IPTV), has led optical-communication systems to higher data rates per wavelength channel, ranging from 10 to 40 and 160 and, at present, even to 640 Gb/s [1]. Degrading effects have become critical aspects of high-performance networks. Among them, polarization mode dispersion (PMD) is perhaps the most pressing problem and has, thus, received a great deal of attention [2-5]. Apart from different formalisms of describing beam polarization and the modal structure of the waveguide, in this paper, a simple approach will be considered, as well. A well known approach is that of a single-mode fiber (SM) which actually refers not to a single, but two modes (physically traveling over the same path). These modes exist due to the fact that light can be presented via two orthogonal polarizations (fig. 1). Therefore, two possible signals could be sent without interference through a single-mode fiber. In a commercial single-mode fiber, the signal consists of both polarizations. However, polarization states are not maintained in the standard SM fiber. During the propagation process, polarization changes randomly unless special precautions are taken.

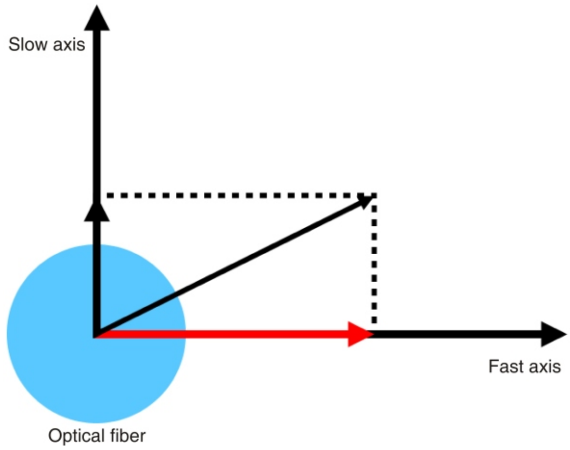

Figure 1. Electrical field vector associated to the propagating optical beam decomposed in two polarization modes (fast and slow)

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A simplified consideration of the problem

Birefringence, as a consequence of material anisotropy, is the characteristic found in materials and some geometries. It means that optical ray paths depend on polarization states in anisotropic materials. Therefore, the power in each optical pulse can be presented via two polarization modes which travel at different velocities, creating a differential group delay (DGD) between the two modes, figs. 2(a) and (b). This process can result in pulse spreading and intersymbol interference. It happens in a regular single-mode fiber which is usually characterized with a very small difference in the refractive index (RI) for each polarization. The produced dispersion is trivial for most applications and labeled as polarization mode dispersion (usually less than 5 ps/nm km). The most general, eliptic polarization mode, can be simplified by means of other forms of polarization (circular, linear, *etc.*). In order to present the propagation process, an optical beam can be described through various formalisms, including Maxwell equations, the material equation, matrix algebra (Jones, Mueller matrices, Stokes parameters), with 2 2 or 4 4, depending on respective crystallographic cases and material anisotropy. Explicitly, the dispersion resulting from birefringent properties of the fiber is labeled "Polarization Mode Dispersion".

The source of "Birefringent Noise" is an important element producing different dispersion parameters. It is also called "Polarization Modal Noise" in some publications. This is a form of modal noise, having the adequate mechanisms. Light propagates along the fiber and, depending on waveguide material and source type, it can change the polarization state. Such changes are produced by variations in fiber composition, geometry, and material fluctuations. The level of power remains approximately constant, but the axes of polarization and the orientation of associated magnetic and electric fields constantly change. It is assumed that there is a polarization sensitive device in the circuit that undergoes significantly higher losses for one polarization mode than the other. These processes produce changes in the total signal power, particularly in respect to various complex signal modulations. Technically, they are the cause of birefringent noises [6-10].

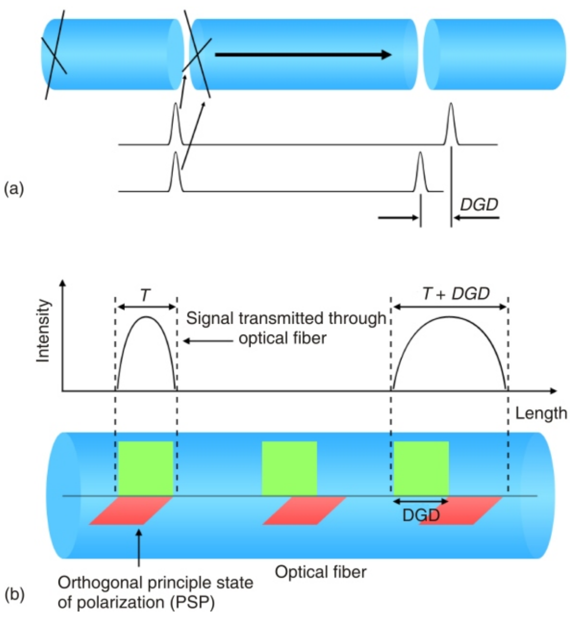

Figure 2. (a) Mode coupling in telecommunication fibers, (b) Transmission of a signal through an optical fiber

The characterization of the PMD

The modification of PMD due to nuclear radiation is just a part of the general investigation of the influence of nuclear radiation on materials, devices, components, biological measurements, diagnostics, and therapy [11-16].

Characterizing fiber dispersion characteristics is a rather complex issue. This complexity is mainly related to resolving a specified dispersion type, in particular, to polarization dispersion. In contrast to obstacles when performing measurements in the field, the characterization in laboratory conditions is less difficult.

Standards, such as ITU-T, IEC, and TIA/EIA, have provided guidelines and recommendations related to PMD and associated measurements. In general, three methods are used for determining the PMD of an optical fiber in the field. They are described by the following TIA/EIA industry standards: the Fixed Analyzer Method (TIA/EIA-455 FOTP-113 standard), the Jones Matrix Method (TIA/EIA -455- FOTP-122A standard), and the Interferometric Method (TIA/EIA -455- FOTP-124A standard) [17-19].

Basically, PMD can be categorized as a first and second order PMD. The first order PMD (FOPMD) refers to pulse spreading. This effect results from the DGD which originates from different signal propagation times of the two orthogonal principal polarization states – PSP, regardless of the transmission wavelength (optimized or not). The FOPMD coefficient, can, thus, theoretically be represented as

$$PMD^{\text{first order}}_{\text{coeffiient}} \quad \frac{1}{\sqrt{l}}\sqrt{\quad \Omega^2(\omega)} \quad \frac{\Delta\tau}{\sqrt{l}} \quad \frac{\text{ps}}{\sqrt{\text{km}}} \qquad (1)$$

where l is the transmission distance, $\Omega\ \omega)$ – the PMD vector, and $\Delta\tau$ – the DGD.

The typical acceptable FOPMD coefficient is from 0.1 ps/(km)$^{1/2}$ to 0.5 ps/(km)$^{1/2}$. As the transmission wavelength changes, the DGD also changes. The FOPMD compensator solves the FOPMD, but residual second order PMD (SOPMD) has to be compensated in another way. Note that the SOPMD coefficient is defined as

$$PMD^{\substack{\text{second order}\\\text{coefficient}}} \quad \frac{2\pi c}{\lambda^2 l}\sqrt{\Omega_\omega^2(\omega)} \quad [\text{ps/nm km}] \quad (2)$$

where $\Omega_\omega^2(\omega)$ is the wavelength dependence of the DGD, λ – the laser wavelength, and l – the transmission distance.

The SOPMD behaves differently from the FOPMD because it is strongly dependent on wavelength [20-22].

Methods of compensation of the PMD

There are a number of ways to remove or compensate PMD characteristics:

(1) The first and most obvious method is to use so-called square waveguides. Square waveguides have characteristics similar to those of cylindrical geometry, and chosen materials often exhibit a minimal birefringence. It is difficult to produce a waveguide layer of adequate thickness.

(2) Appropriate cutting across the array waveguide region enables the insertion of components (polarization plates – $\lambda/2, \lambda/4$, *etc.*). The PMD is an obstacle that requires a retardation plate with an index of refraction close to the waveguide material. This can be solved for silica and lithium niobate based waveguides, but remains a problem for devices made in InP and similar materials.

(3) Careful design of the free space coupler at the receiver side of the device can compensate for the PMD introduced into the waveguides. However, this introduces severe limits on the total wavelength device operating range.

(4) The use of sectioned waveguides with different PMD characteristics in each section creates a balance.

(5) Splitting the input signal into its orthogonal polarizations and their injection into the device at different points in the input free space region.

EXPERIMENTAL

Our samples of interest were optical fibers of a commercial type in the shape of a coil 1000 m long (according to ITU-T G.652), as shown in figs. 3(a) and 3(b), and tab. 1. The sample was positioned in a calibration stand and placed in the radiation field for the purpose of irradiation. The irradiation was performed in the Secondary Standard Dosimetry Laboratory of the Vinča Institute of Nuclear Sciences, Belgrade, Serbia, using source ^{60}Co of activity 124.1 TBq (28. 8. 1990). The energies of γ-radiation of ^{60}Co were 1.173 MeV and 1.332 MeV. The diameter of the coil was 100 mm and, due to the hollow central area, the attenuation in the coil can be neglected. During irradiation, the coil central axis was perpendicular to the radiation beam central axis. The coil side oriented toward the radiation source was at a distance of 45 cm, while the opposite side of the coil was at a distance of 55 cm. Air kerma rate at a distance of 45 cm was 13 Gy/h. Taking into consideration that air kerma decreases due the inverse square law, the average dose for the entire coil was 11.6 Gy/h. For an irradiation time of 3 hours, the total dose was 34.8 Gy. Irradiation was performed in controlled environment conditions (atmospheric pressure and room temperature of 25 °C).

Figure 3(a). Coiled monomode optical fiber sample in front of ^{60}Co source housing

Figure 3(b). The details of the measuring place outside of the exposition area

Table 1. Main characteristics of the optical fiber

Characteristics	Specified values	Unit
Fiber type	G.652.D	
Attenuation 1310 nm	0.40	dB/km
Attenuation 1383 nm	0.40	dB/km
Attenuation 1550 nm	0.28	dB/km
Attenuation uniformity	0.2	dB
Cut-off wavelength	1150-1330	nm
Dispersion 1285-1330 nm	3.5	ps/nm km
Dispersion 1550 nm	18	ps/nm km
Zero dispersion	1310	nm
Dispersion mode polarization	0.2	ps/$\sqrt{\text{km}}$

Measurements of the PMD were conducted by devices ANRITSU CMA 5000 including module PMD 1600. All measurements in the experiment were performed in three steps. The first step was to measure the PMD coefficient before the irradiation. The second step was to conduct the measurements during the three irradiation intervals. Each time interval lasted one hour during which the measurements were successively performed in ten minutes. The third step consisted of measurements that were performed during the time period of five days, approximately (160 hours). These measurements were completed after the fiber's exposure.

The characteristics of the laser power source included in measurement equipment were presented in tab. 2.

Due to the fact that the sample coil was 1000 m long, the measurement system included a 5000 m test fiber (FC/UPC- FC/UPC, SM, 5 km) connected in line with the sample. All measurement devices, connectors and test fibers were placed out of the experimental room. The connection with the sample fiber was maintained through special wall apertures. The exposure area was 100 cm^2 (fig. 4).

The PMD of a fiber is completely described once the differential group delay (DGD) and the principal states of polarization (PSP) are characterized as functions of wavelength. The terms of PMD and DGD are often used interchangeably, although the term PMD describes the phenomenon while DGD describes its magnitude [17-22]. The graphic user interface of the measured PMD parameters is shown in fig. 5.

Table 2. Main characteristics of laser source

Polarization mode dispersion source specification	
Output power	–1 dBm
Related dynamic range*	52 dB
Minimum measurable PMD	0.06 ps

* Given for 1 ps PMD. Dynamic range for 10 ps PMD is 8 dB below this value

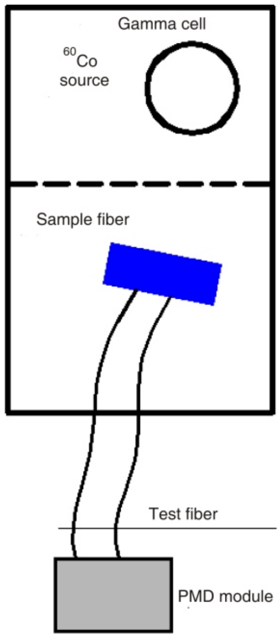

Figure 4. The measurement scheme of the experiment for the PMD

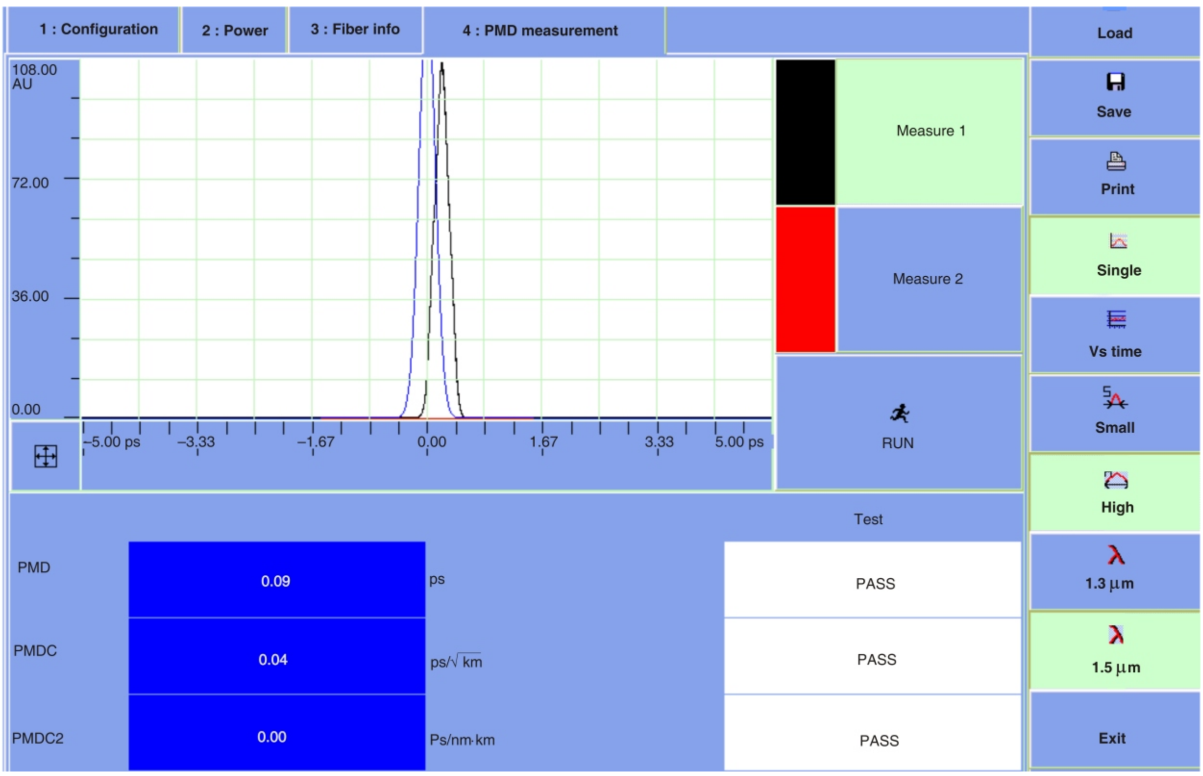

Figure 5. Graphic user interface of the measured PMD parameters

Note that polarization formalisms are different. They include the matrix calculus, Stokes vectors, as well as the Mueller matrix, descriptions specifically developed for fibers [23-28].

Interferometry is a field application of the PMD measurement technique. It is designed to measure high PMD in installed fiber cables. It is characterized by a high tolerance to fiber movement and a fast measurement time.

The PMD is based on a statistics of measurements which are also sensitive to the external environment. Thus, it is recommended to perform various measurements at different time intervals. In this way, the long term fluctuation of the DGD can be monitored, providing better records of the optical fiber.

This method involves the measurement of the light propagation time along the fiber at various wavelengths. In our investigation two wavelengths of 1310 nm and 1550 nm were applied. The results of the computed PMD coefficients are presented in figs. 6(a)-(d) and of PMDC in figs. 7(a)-(d).

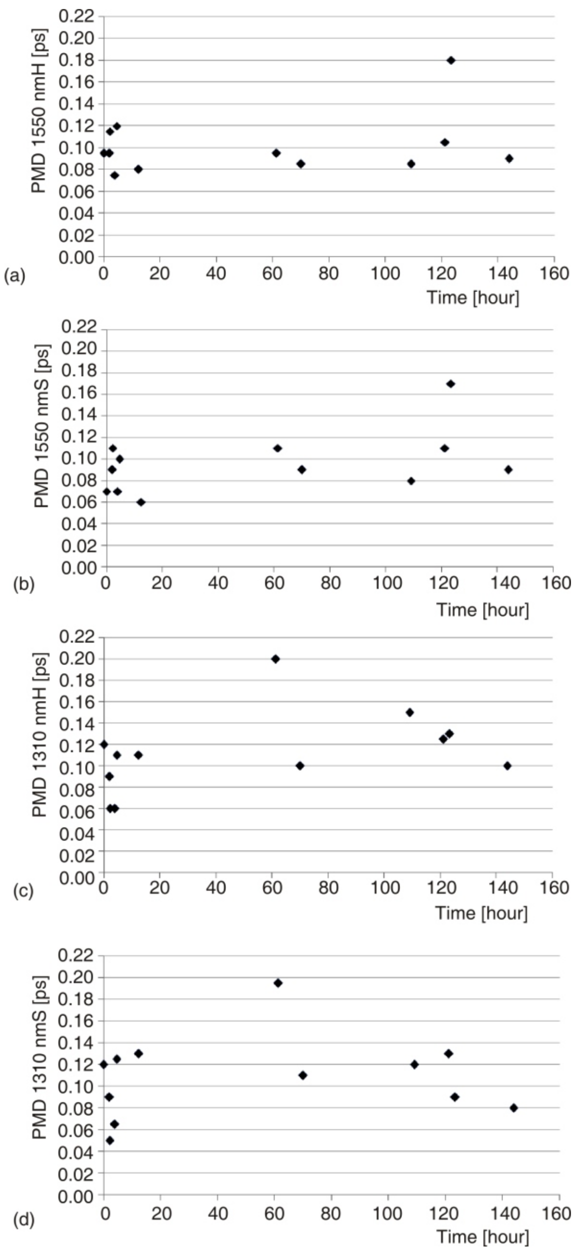

Figure 6. The PMD *vs*. time: (a) and (b) for wavelength 1550 nm, (c) and (d) for 1310 nm. "H" and "S" sign for high and small measuring pulse width

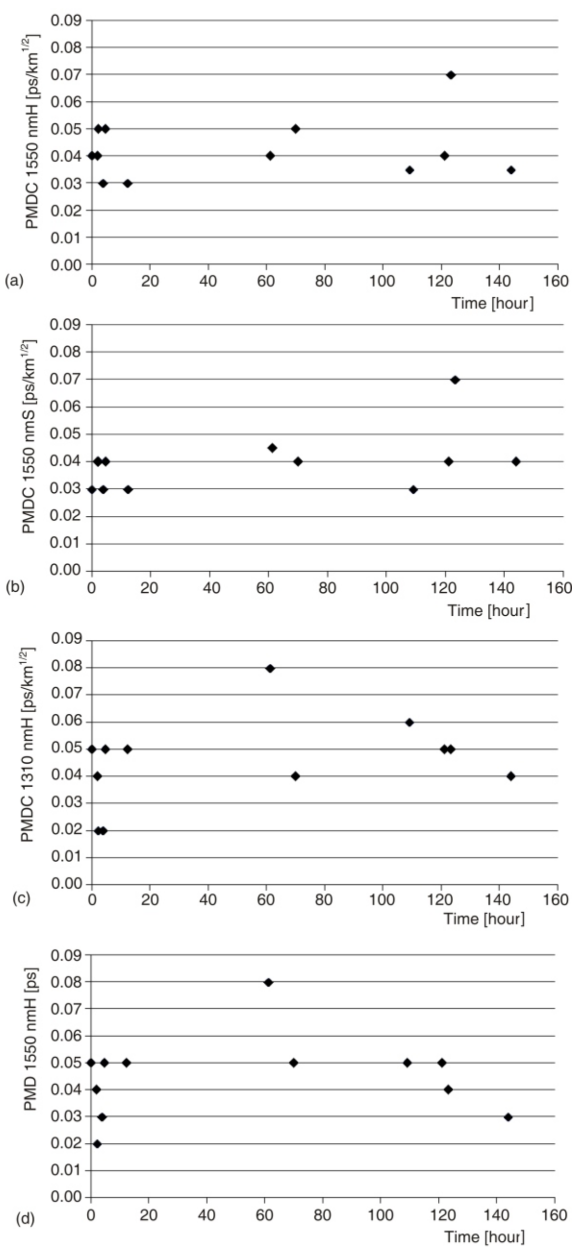

Figure 7. The PMDC *vs*. time: (a) and (b) for wavelength 1550 nm, (c) and (d) for 1310 nm. "H" and "S" sign for high and small measuring pulse width

RESULTS AND DISCUSSION

In this paper, the fiber parameters PMD were measured over several time periods. According to the ITU G.652 standard, optical fibers were exposed to gamma radiation of ^{60}Co. During the exposure, all characteristics were monitored in real time and recordings collected every ten minutes. The period of time in which the annealing was monitored was up to160 hours. The short time response was found as soon as the exposure started. After that, changes were noticed when irradiation was included. These changes were produced by both increased and decreased PMD magnitudes. The changes were smaller for the range of 1550 nm than for that of 1310 nm. Note that the optical fiber samples are optimized for the transmission range of 1550 nm. The same procedure can be applied to other types of optical fibers, developed for commercial and non-commercial purposes. The behavior of single and multimode fibers can present another interesting point of investigation, with the same equipment. Note that the problem could arise if the various sample fibers are not standardized by characteristic parameters. In case of different indices of refraction *i. e.* $n(r)$, dispersion measuring data will be changed.

CONCLUSIONS

Theoretically speaking, dispersion can be interpreted diversely, depending on the theoretical and technical point of view. Among other things, the considering linear and non-linear phenomena is of great interest. The variations of signal amplitudes (from low to high) additionally lead to modulation of material with the associated electric and magnetic fields. This provokes anisotropy of material in the modern sense with ultra short laser pulses. Furthermore, normal, and anomalous dispersions with non-linear effects attract considerable attention. Technically speaking, measurement devices with optical fibers are sophisticated equipment. Therefore, in this paper, we present only cases of low power optical signals and the behavior of the main technical characteristics for transmission, as well as their changes in fibers exposed to particular nuclear radiation.

The results of our investigations are: the data rate per optical channel increases, solving the PMD-induced degrading effects in such a way that the PMD emulation and compensation techniques become more desirable. This requires effective and fast PMD monitoring and PMD control, as well. In addition, there are many examples of other degrading effects, such as fiber non-linearities and polarization-dependent, as well as wavelength-dependent losses. Some of them may interact with PMD and make the situation even worse.

By observing the microstructural point of view, macroscopic parameters and theoretical simulation could be implemented for fundamental advances in materials and communication systems design. Relatively low power laser sources were used in this research. Nowadays, high and ultrafast lasers (femto and atto second) are used in optical communication systems. Utilizing them will certainly lead to new theoretical and experimental tasks.

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УТИЦАЈ ГАМА ЗРАЧЕЊА НА ПОЛАРИЗАЦИОНУ ДИСПЕРЗИЈУ ОПТИЧКИХ ВЛАКАНА У ТЕЛЕКОМУНИКАЦИЈАМА

Технологија оптичких влакана константно се развија и постаје главна компонента у савременим комуникацијама, медицини и индустрији. Оптичка влакна, њихови спојеви и компоненте система имају главну улогу у преносу оптичких сигнала, у телекомуникацијама, преносу снаге или у процесима, где се користе као сензори. Две најважније пропагационе карактеристике оптичког сигнала у влакну су слабљење и дисперзија. Могућност контроле ових параметара је врло важна за постизање захтеваног квалитета преноса. У овом раду, анализирали смо одређена питања у вези са оптичким влакнима и наше експерименте са утицајем гама зрачења ^{60}Co, на пропагационе карактеристике влакана, као што је поларизациона дисперзија.

Кључне речи: оптичко влакно, радијациони ефект, поларизациона дисперзија, утицај на околину, гама озрачавање